An status update on the Swampland

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22nd June 2020, Be.HEP Annual meeting

Université Libre de Bruxelles

Summer Solstice... And the Swampland

Outline

We will journey into the Swampland...

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We will journey into the Swampland...

1. The Swamp...what?
    - Why String Theory comes with a **Landscape of vacua.**
    - Eft's outside of the Landscape lie in the **Swampland.**
    - How to find your own conjecture.

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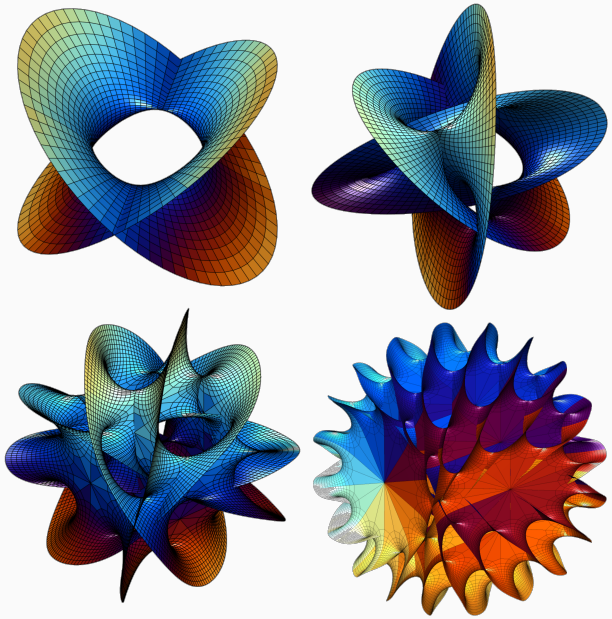
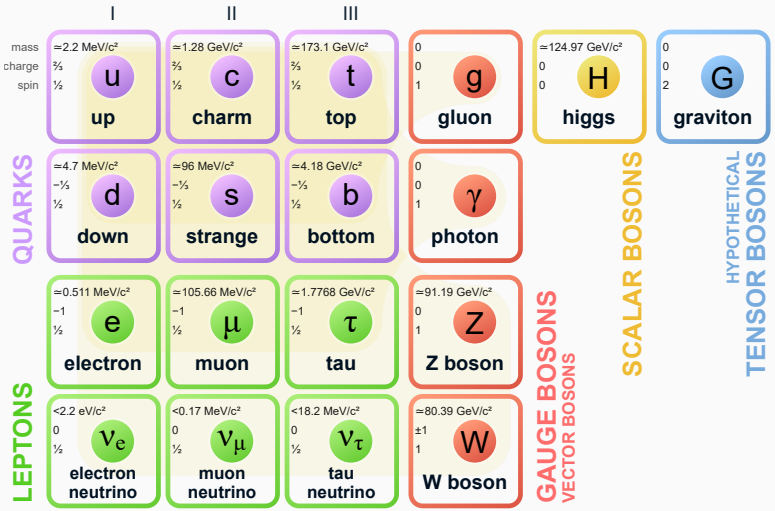
We will journey into the Swampland...

1. The Swamp...what?
   - Why String Theory comes with a **Landscape of vacua.**
   - Eft's outside of the Landscape lie in the **Swampland.**
   - How to find your own conjecture.
2. Charting the Swampland: **A landscape of conjectures.**
   $\rightarrow$ A good map: (Palti, 2019)
3. Looking for a **unifying principle.**
4. **Phenomenological** applications: A new (provocative) framework?

From String Theory to our universe: The Landscape...

Put a String Theory on a CY_3...





...And get a Universe

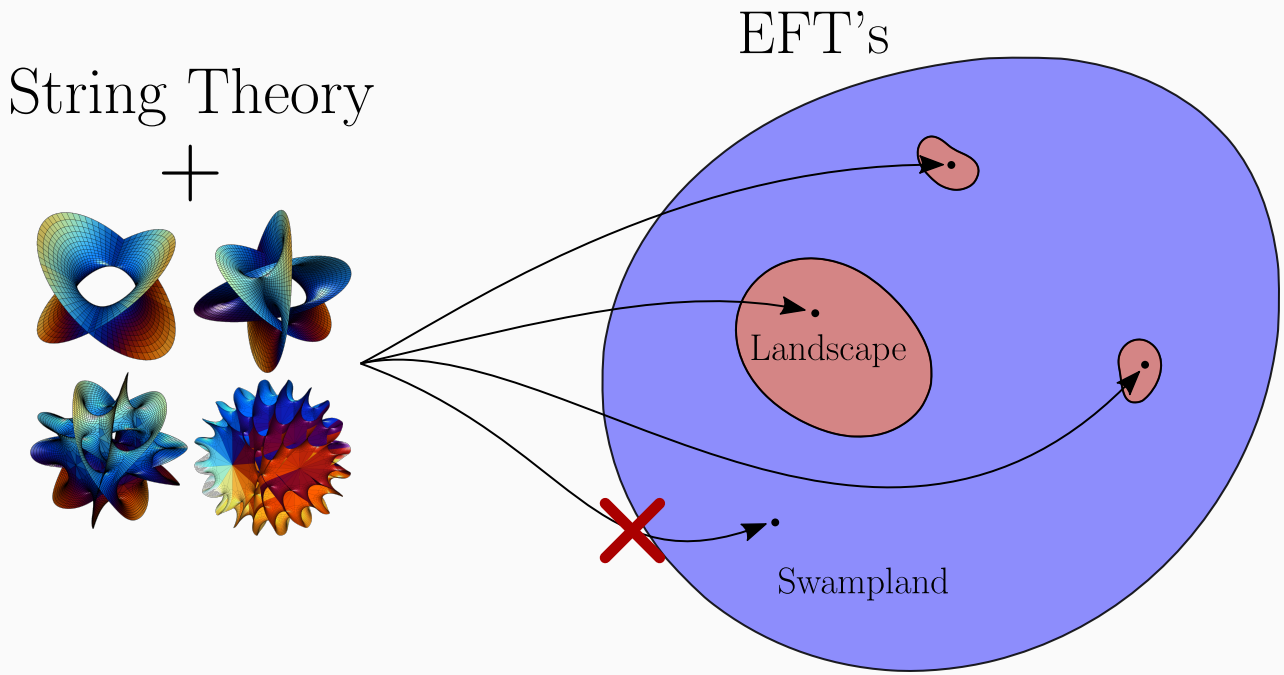
In fact a whole Landscape of Universes

...And the Swampland

- Can we get **any universe**? (a.k.a. any (EFT)) $\Rightarrow$ **NO**

...And the Swampland

- Can we get **any universe**? (a.k.a. any (EFT)) $\Rightarrow$ **NO**
- EFT's reachable from String Theory are in the **Landscape**. Anything else, in the **Swampland**.



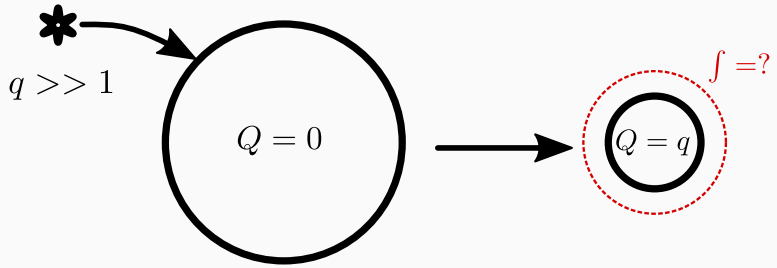
- We want to chart the **boundaries**. One conjectures **criteria** to specify this boundary.

How to find your own Conjecture?

Evidence from Quantum Gravity (Global Symmetries)

A black hole (BH) argument (Banks & Dixon, 1988)

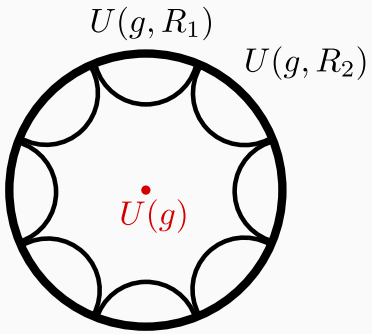
- Take theory with $U(1)$ global symmetry. An evaporating BH can't shed its charge!



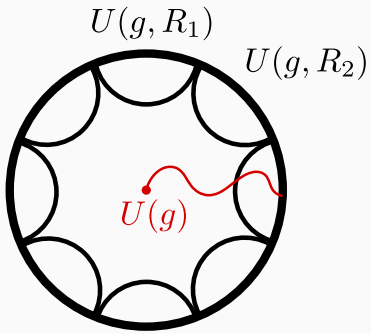
- Global symmetries are inconsistent with no-hair theorem + Hawking evaporation.

An AdS/CFT Proof (Harlow & Ooguri, 2018)

- A global symmetry in the CFT is splittable. A local operator transforming under a global symmetry in the bulk can't be reconstructed from the boundary.



Global Symmetry



Gauge Symmetry

Evidence from String Theory (Global Symmetries)

- String Theory is the best understood theory of Quantum Gravity (QG). One can consider it an **"experimental" arena for QG properties.**
- **Caveat:** We might be looking under the **String Lamppost.**
- Remarkably, many "experimental" observations can be argued for using general QG arguments.
- **In String compactifications one finds:**
  1. All symmetries are gauged by the diffeomorphisms in compact dimensions.
  2. All representations of a gauge symmetry are realized.
  3. Gravity is weaker that other gauge forces.
  4. Non-SUSY stable vacua are, at best, extremely sparse.
  5. ...

A Landscape of Conjectures

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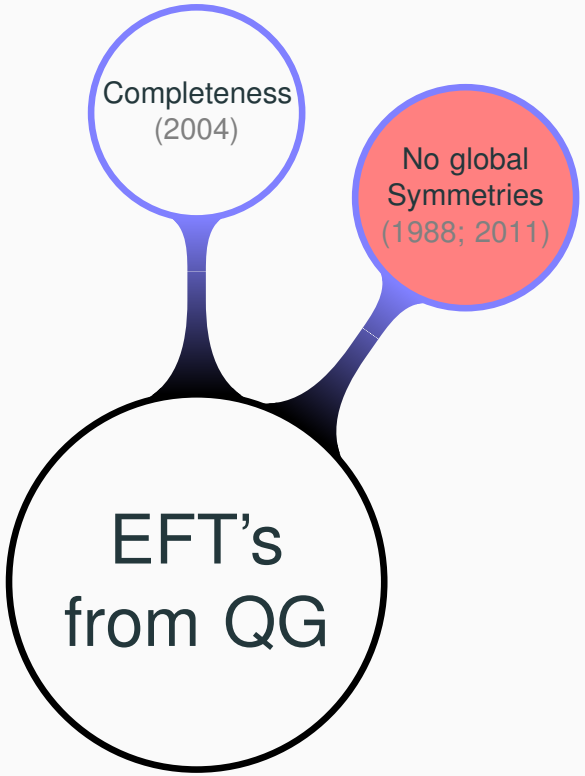

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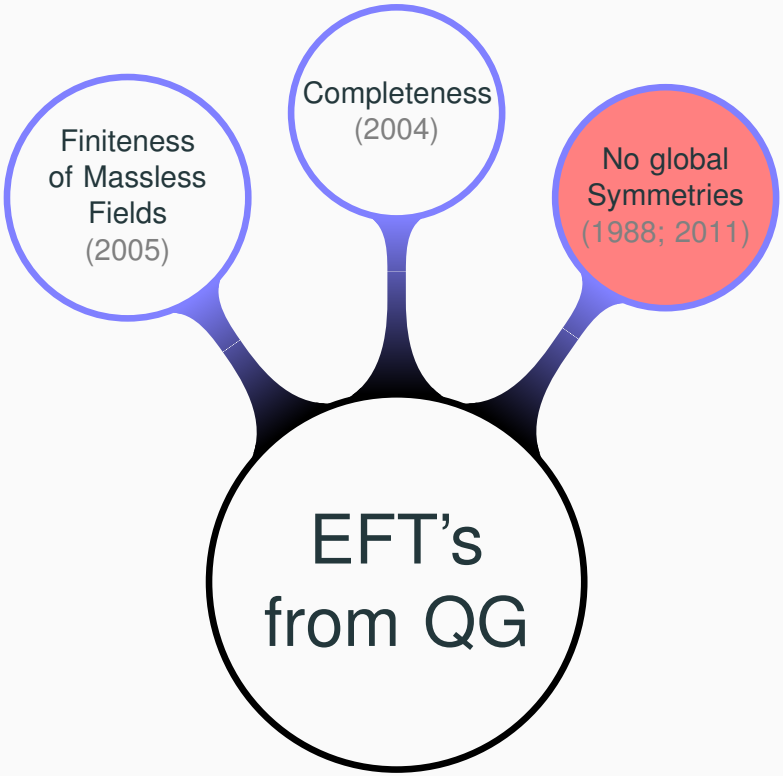

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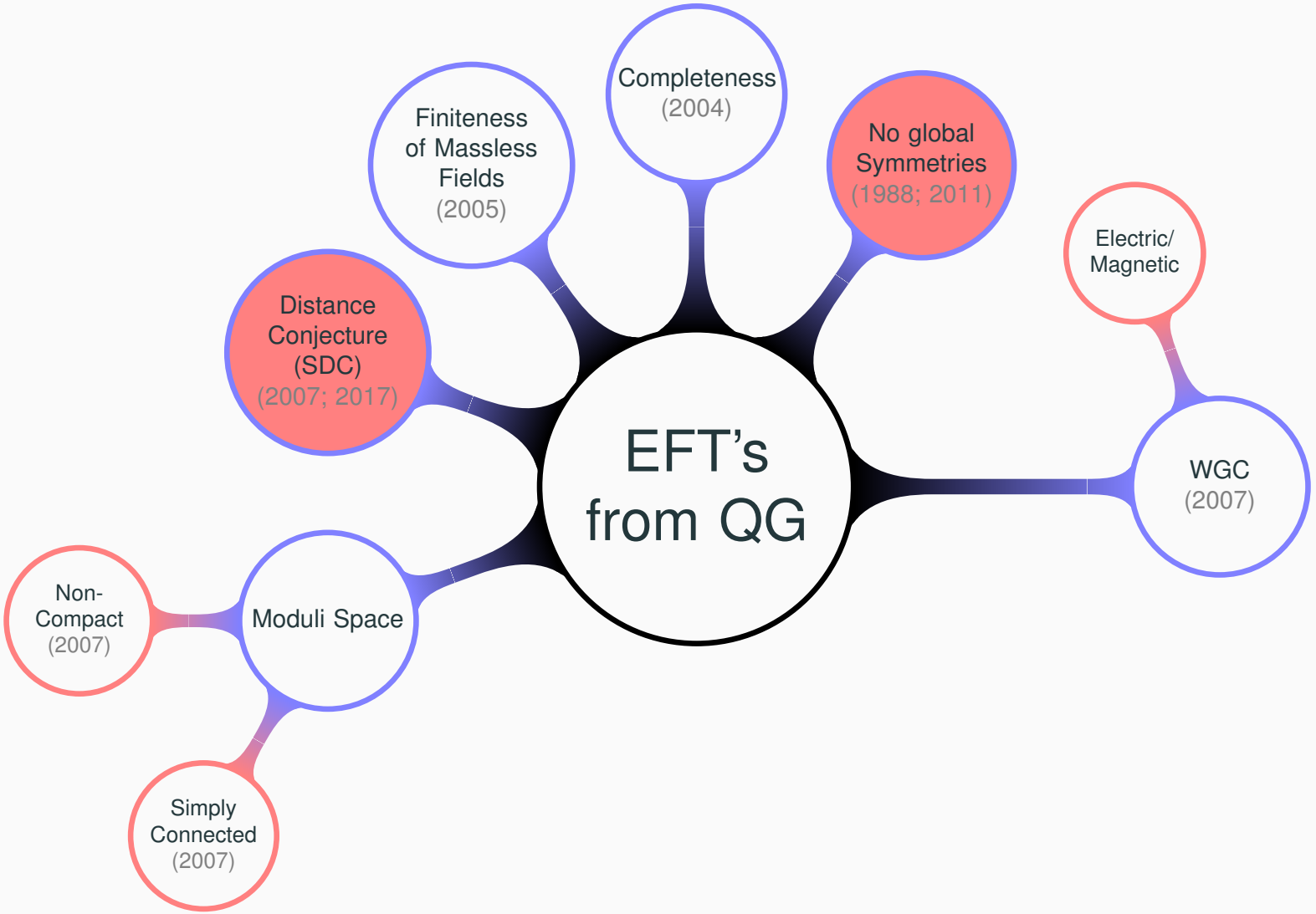

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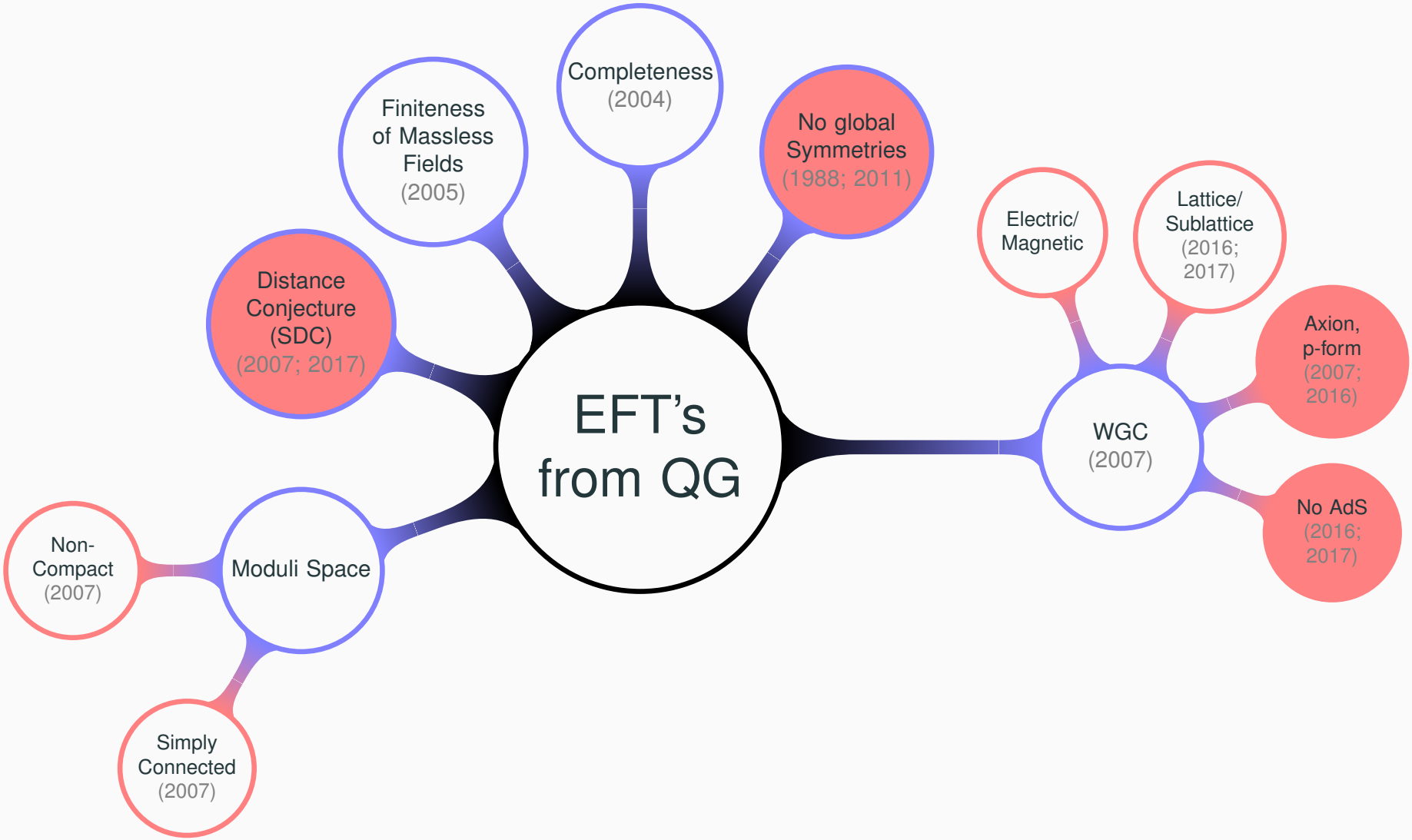

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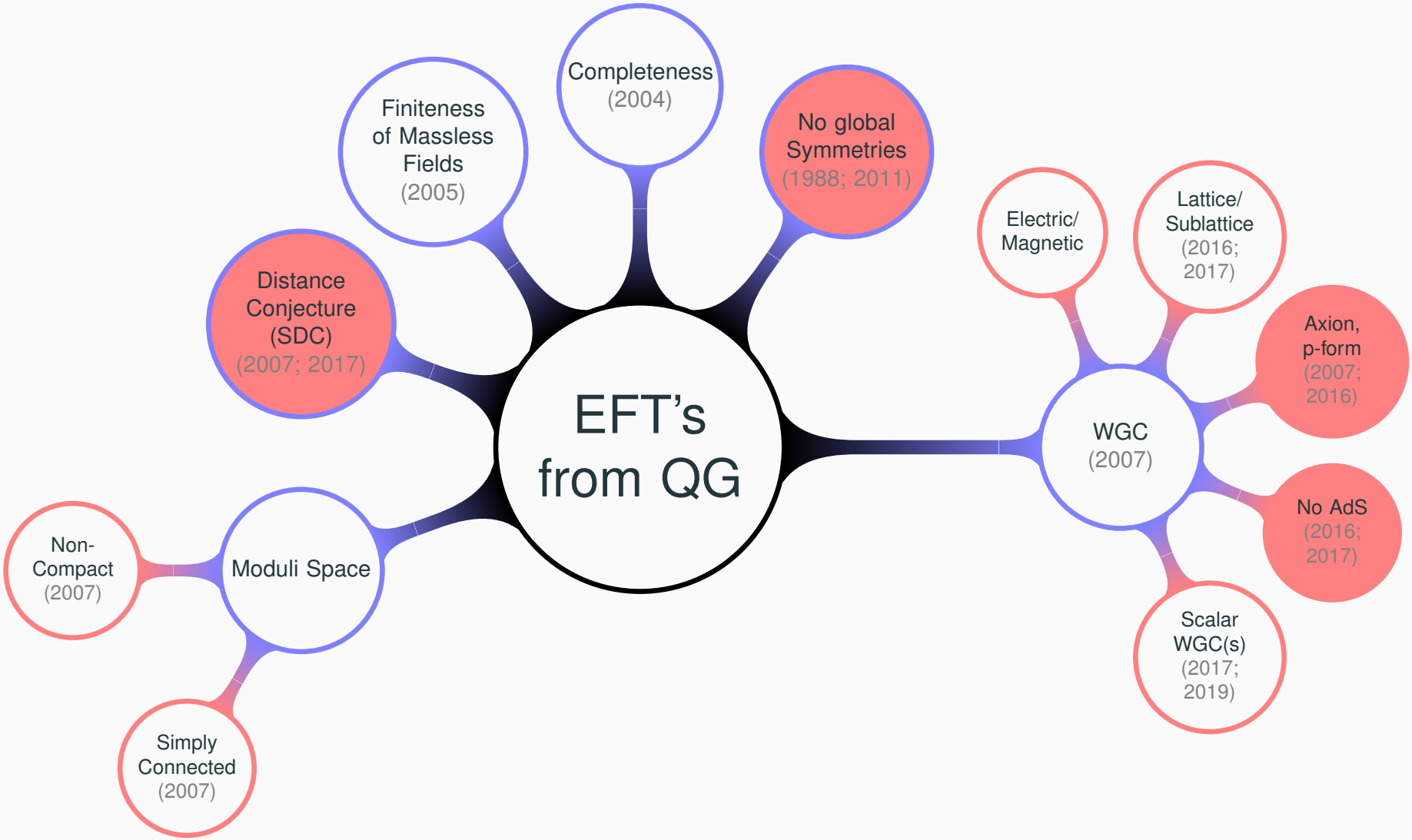

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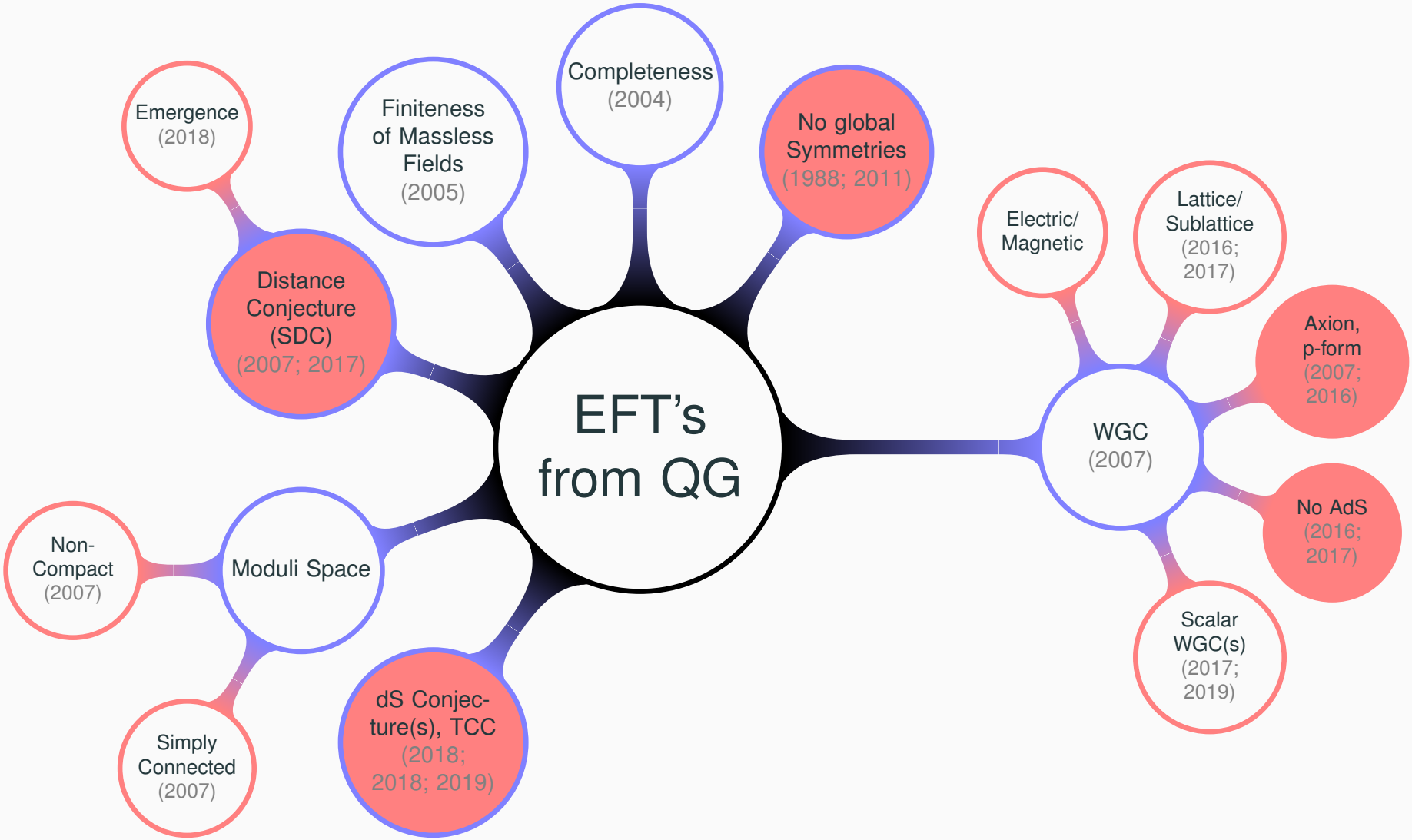

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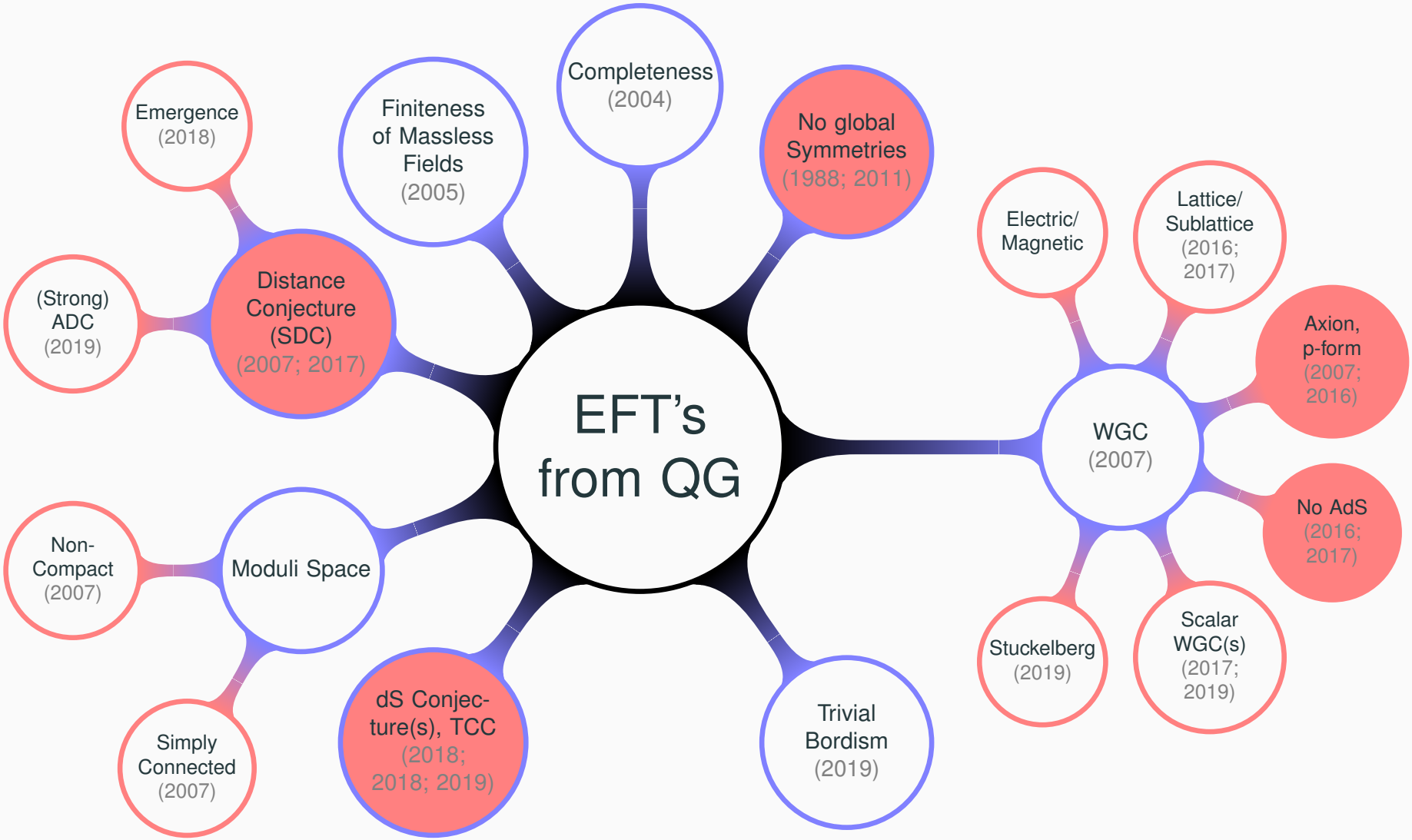

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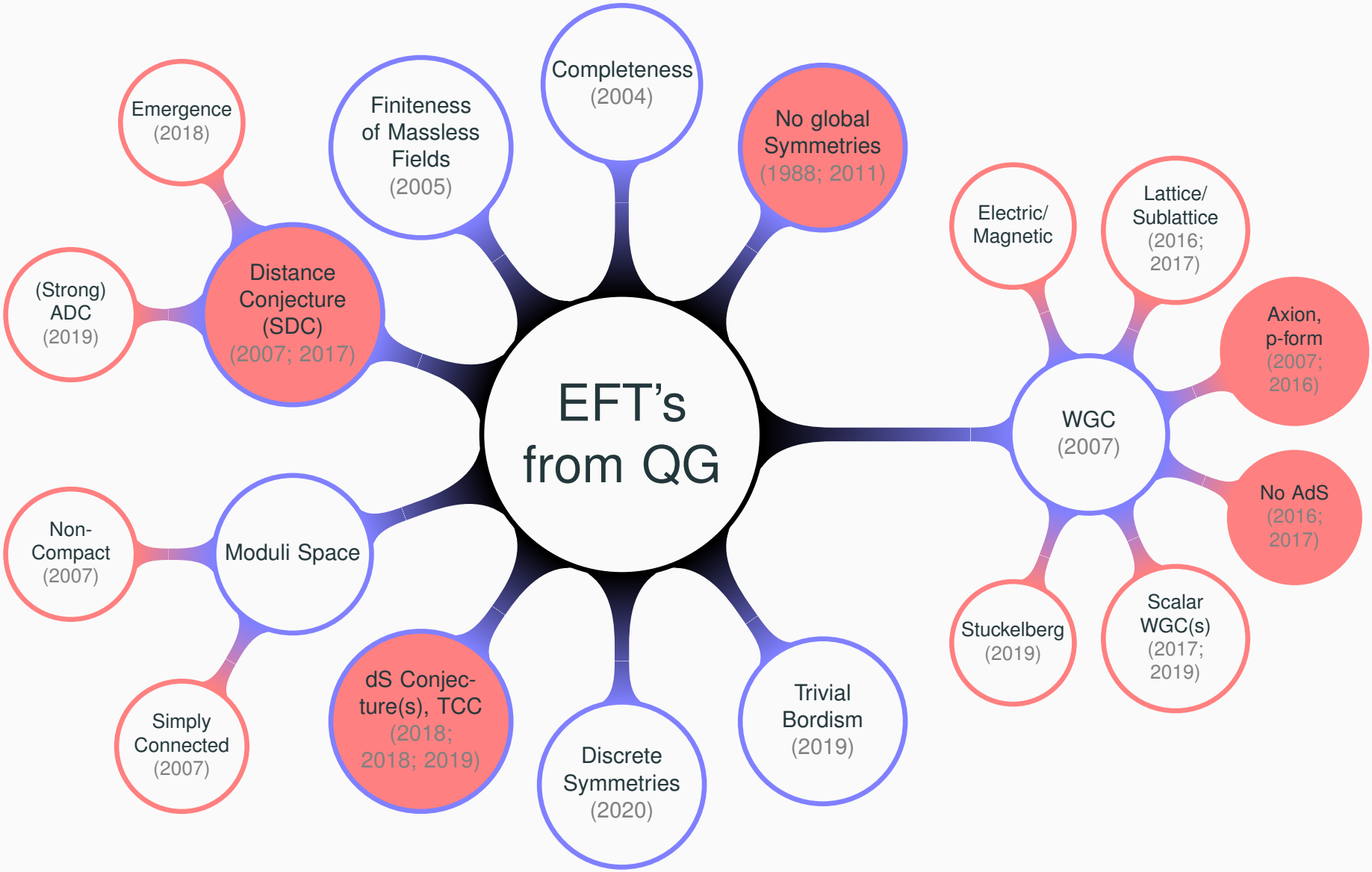
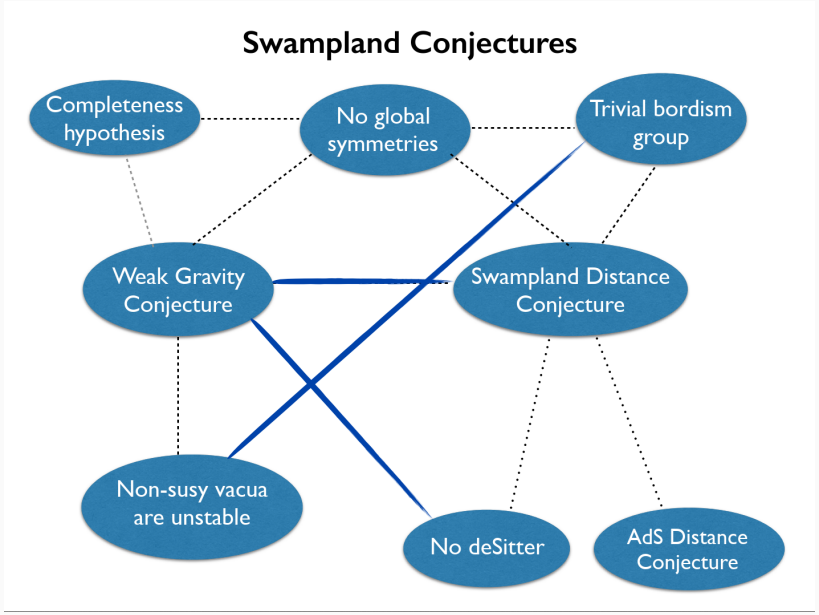


Doesn’t it look similar?

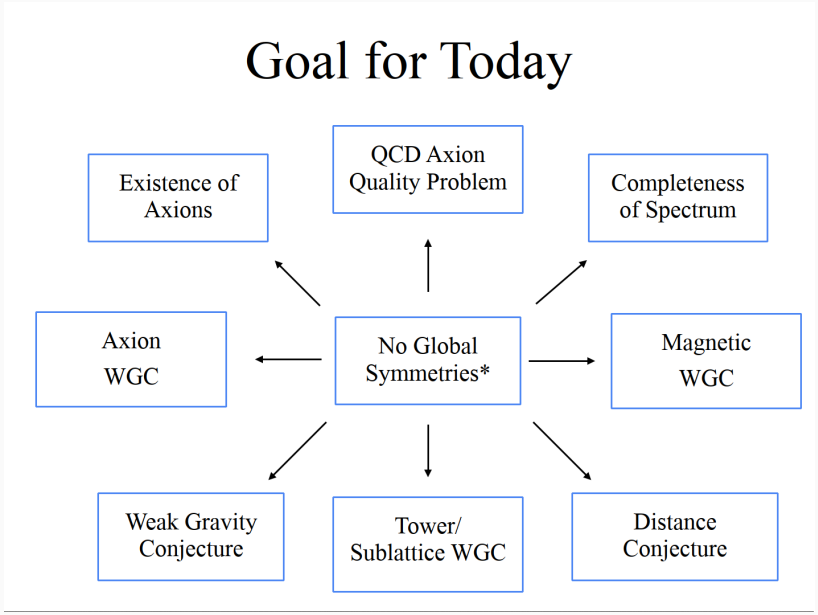
Looking for a Unifying Principle

Looking for a Unifying Principle

Slides from String Pheno 2020



Irene Valenzuela



Tom Rudelius

Looking for a Unifying Principle

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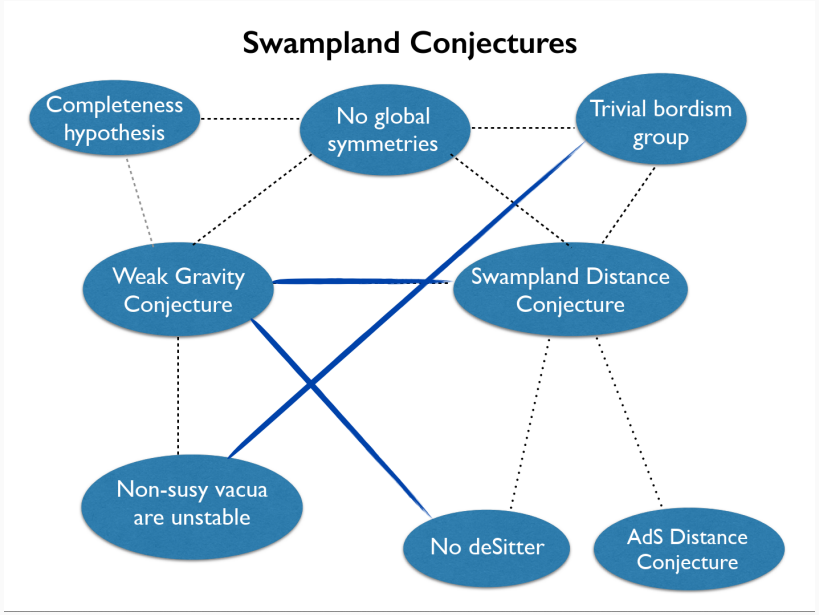

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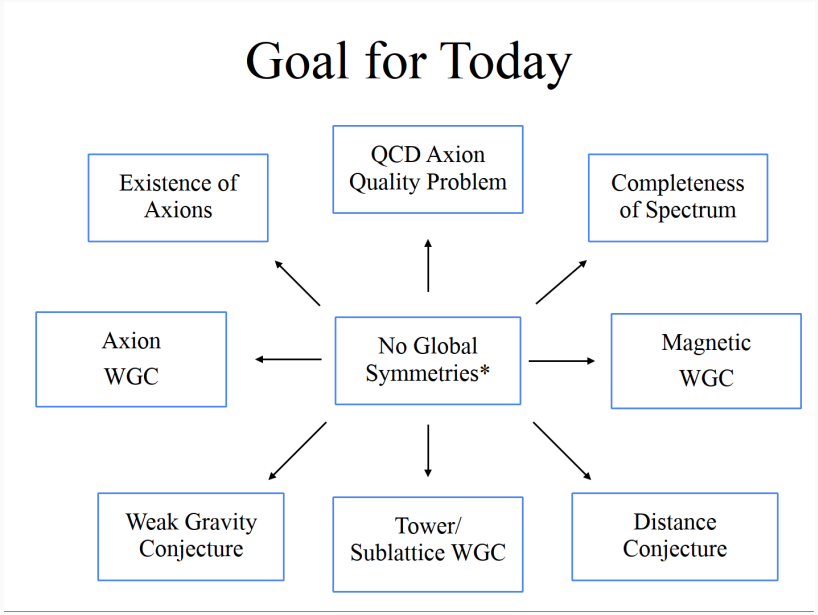
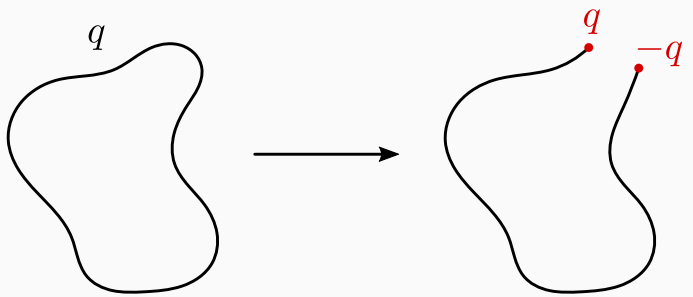


Tom Rudelius

- Emergence
- Global Symmetries
- Anomalies inside dynamical objects of the theory
- ...

Global Symmetries are powerful!

- Absence of global symmetries is more powerful that meets the eye.
- Absence of **Generalized Global Symmetries** can be used to deduce many conjectures:
  1. **Completeness of spectrum** to explicitly break them.(Rudelius & Shao, 2020)



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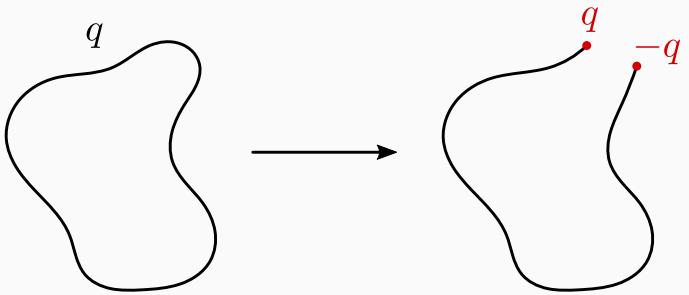

  2. **Axions** to gauge Chern-Weil Global Symmetries. $\theta Tr(F \wedge F)$ analog to $A_\mu J^\mu$. See Tom Rudelius talk at StringPheno 2020.

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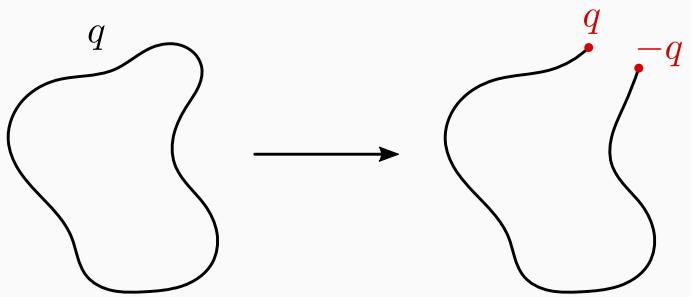
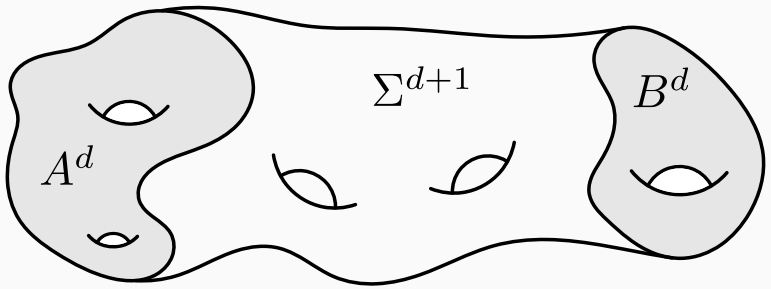


  2. **Axions** to gauge Chern-Weil Global Symmetries. $\theta Tr(F \wedge F)$ analog to $A_\mu J^\mu$. See Tom Rudelius talk at StringPheno 2020.
- Compactification with a non-trivial bordism can be thought as a global symmetry. All compactifications must be **trivial in bordism.**(McNamara & Vafa, 2019)



Some Interesting Conjectures for Pheno

A new (provocative) framework?

In phenomenology we assume the **Wilsonian framework:**

- SM unifies with Quantum Gravity at the Planck Scale.
- As we go down to an EFT, irrelevant operators decouple. The **UV decouples from the IR.**
- We can ignore Quantum Gravity effects at low energies.

The Swampland program says the opposite:

- **In Quantum Gravity UV and IR are connected.** E.g. Black Holes.
- Some EFT's may not be UV completed to Quantum Gravity.

No non-SUSY AdS vacua.

- In a consistent theory of Quantum Gravity there are **no stable non-SUSY AdS vacua.** (Ooguri & Vafa, 2017)
- EFT's belonging to the swampland must be consistent under deformations allowed by QG. In particular compactification.
- **Compactify the SM in a circle!** It turns out that it can give 3d (Non-SUSY) AdS depending on neutrino physics.
- For instance, **Majorana neutrinos** lead to AdS. They are **not allowed.**
- Lightest Dirac neutrinos must be light(Ibanez *et al.*, 2017; Hamada & Shiu, 2017):

$$m_\nu < 7.7\text{meV (NH)}, \quad m_\nu < 2.1\text{meV (IH)} \tag{1}$$

- A lower bound on the cosmological constant $\Lambda \gtrsim m_\nu^4$.

The Axion WGC

- An axion is an scalar field with a perturbative shift symmetry broken by a non-perturbative superpotential generated by e.g. instantons:

$$\mathcal{L} \in -f^2(d\phi)^2 + \Lambda^4 \sum_q e^{-qS}(1 - \cos(q\phi)) \tag{2}$$

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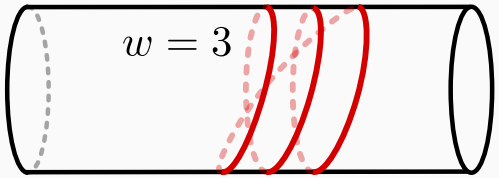
- **Axion WGC:** *An axion must couple to an instanton with action S s.t.* $\boxed{fS \leq M_p}$ (Arkani-Hamed *et al.*, 2007)
- For perturbative control: $S > 1$, which implies $f \leq M_p$.
- The bound on the periodicity of the axion limits its physical applications (**natural inflation, relaxion...**).

The Swampland Distance Conjecture

- **As one moves in Moduli Space, a tower of states becomes exponentially light,**

$$M_f < M_i e^{-\alpha \frac{d_{i,f}}{M_p}} \tag{3}$$

- This implies that, if one varies an scalar field, the EFT becomes inconsistent as the distance approaches the mass scale.
- The prototypical example is Kaluza-Klein compactification with strings.



$$M^2 = \left(\frac{n}{R}\right)^2 + \left(\frac{wR}{\alpha'}\right)^2$$

- It can be seen as a statement about the behaviour of asymptotic/singular regions in Moduli Space.
- Constraining whenever one has **large field displacements.**
- It can be used to constrain **light Stuckelberg fields.**(Reece, 2019)

The (Refined) DeSitter Conjecture

- There is a *controversial* claim that, any scalar potential would be required to satisfy:(Obied *et al.*, 2018; Ooguri *et al.*, 2018; Garg & Krishnan, 2018)

$$|\nabla V| \geq cV \quad \text{or} \quad \min(\nabla_i \nabla_j V) \leq -c' V \tag{4}$$

- A consequence of this statement is that **metastable DeSitter vacua,** satisfying,

$$\nabla V = 0, \quad \nabla^2 V < 0, \quad V > 0 \tag{5}$$

  would **not be allowed in QG.**

- It has been used to argue for Quintessence, which is itself very difficult to achieve in QG.
- It may also have implications on Inflation. The precise implications have been studied in the literature.

Conclusions

- String Theory comes with a **Landscape of vacua.**
- We believe the Landscape is a tiny subset of the EFT's. Outside of it lies **the Swampland.**
- One characterizes the boundary of the Landscape **conjecturing features** of it.
- In the last years connections between the conjectures are appearing. Are there **underlying principles?**
- Quantum Gravity may affect non-trivialy the IR. An opportunity for **QG phenomenology!?**

Arkani-Hamed, Nima, Motl, Lubos, Nicolis, Alberto, & Vafa, Cumrun. 2007.
The String landscape, black holes and gravity as the weakest force.
JHEP, **06**, 060.

Banks, Tom, & Dixon, Lance J. 1988.
Constraints on String Vacua with Space-Time Supersymmetry.
Nucl. Phys., **B307**, 93–108.

Banks, Tom, & Seiberg, Nathan. 2011.
Symmetries and Strings in Field Theory and Gravity.
Phys. Rev., **D83**, 084019.

Bedroya, Alek, & Vafa, Cumrun. 2019.
Trans-Planckian Censorship and the Swampland.
arXiv e-prints, Sep, arXiv:1909.11063.

Buratti, Ginevra, Calderon, Jose, Mininno, Alessandro, & Uranga, Angel M. 2020.
Discrete Symmetries, Weak Coupling Conjecture and Scale Separation in AdS Vacua.

JHEP, **06**, 083.

Freivogel, Ben, & Kleban, Matthew. 2016.
Vacua Morghulis.

Garg, Sumit K., & Krishnan, Chethan. 2018.
Bounds on Slow Roll and the de Sitter Swampland.

Gonzalo, Eduardo, & Ibáñez, Luis E. 2019.
A Strong Scalar Weak Gravity Conjecture and Some Implications.
JHEP, **08**, 118.

Grimm, Thomas W., Palti, Eran, & Valenzuela, Irene. 2018.
Infinite Distances in Field Space and Massless Towers of States.
JHEP, **08**, 143.

Hamada, Yuta, & Shiu, Gary. 2017.
Weak Gravity Conjecture, Multiple Point Principle and the Standard Model Landscape.
JHEP, **11**, 043.

Harlow, Daniel, & Ooguri, Hirosi. 2018.

Symmetries in quantum field theory and quantum gravity.
10.

Heidenreich, Ben, Reece, Matthew, & Rudelius, Tom. 2016.
Sharpening the Weak Gravity Conjecture with Dimensional Reduction.
JHEP, **02**, 140.

Heidenreich, Ben, Reece, Matthew, & Rudelius, Tom. 2017.
Evidence for a sublattice weak gravity conjecture.
JHEP, **08**, 025.

Ibanez, Luis E., Martin-Lozano, Victor, & Valenzuela, Irene. 2017.
Constraining Neutrino Masses, the Cosmological Constant and BSM Physics from the Weak Gravity Conjecture.
JHEP, **11**, 066.

Klaewer, Daniel, & Palti, Eran. 2017.
Super-Planckian Spatial Field Variations and Quantum Gravity.
JHEP, **01**, 088.

Lüst, Dieter, Palti, Eran, & Vafa, Cumrun. 2019.
AdS and the Swampland.

McNamara, Jacob, & Vafa, Cumrun. 2019.
Cobordism Classes and the Swampland.
9.

Obied, Georges, Ooguri, Hirosi, Spodyneiko, Lev, & Vafa, Cumrun. 2018.
De Sitter Space and the Swampland.

Ooguri, Hirosi, & Vafa, Cumrun. 2007.
On the Geometry of the String Landscape and the Swampland.
Nucl. Phys., **B766**, 21–33.

Ooguri, Hirosi, & Vafa, Cumrun. 2017.
Non-supersymmetric AdS and the Swampland.
Adv. Theor. Math. Phys., **21**, 1787–1801.

Ooguri, Hirosi, Palti, Eran, Shiu, Gary, & Vafa, Cumrun. 2018.
Distance and de Sitter Conjectures on the Swampland.
Phys. Lett., **B788**, 180–184.

Palti, Eran. 2017.
The Weak Gravity Conjecture and Scalar Fields.

JHEP, **08**, 034.

Palti, Eran. 2019.
The Swampland: Introduction and Review.

Polchinski, Joseph. 2004.
Monopoles, duality, and string theory.
Int. J. Mod. Phys., **A19S1**, 145–156.
[,145(2003)].

Reece, Matthew. 2019.
Photon Masses in the Landscape and the Swampland.
JHEP, **07**, 181.

Rudelius, Tom, & Shao, Shu-Heng. 2020.
Topological Operators and Completeness of Spectrum in Discrete Gauge Theories.
6.

Vafa, Cumrun. 2005.
The String landscape and the swampland.